GLOBAL LOCALIZATION OF AN INDOOR MOBILE ROBOT WITH A SINGLE BASE STATION

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Abstract

The navigation tasks in advanced home robotic applications incorporating reliable revisiting strategies are dependent on very low cost but nevertheless rather accurate localization systems. In this paper a localization system based on the principle of trilateration is described. The proposed system uses only a single small base station, but achieves accuracies comparable to systems using spread beacons and it performs sufficiently for map building. Thus it is a standalone system and needs no odometry or other auxiliary sensors. Furthermore a new approach for the problem of the reliably detection of areas without direct line of sight is presented. The described system is very low cost and it is designed for use in indoor service robotics. The paper gives an overview on the system concept and special design solutions and proves the possible performances with experimental results.

Keywords: autonomous mobile robots, robot navigation, low cost localization, trilateration, indoor, single base station.

1. INTRODUCTION

Robotics in commercial home applications is getting more and more in focus. Different autonomous mobile robot platforms are already available for several service tasks as well as “intelligent” toys. Most of them do not use a global localization system to perform their tasks and they have therefore limited capabilities.

In the case of indoor robotics on a flat surface the localization system needs only a 2D position determination with limited range. As examined by the authors the accuracies needed for map building and planned navigation in indoor surroundings are in the order of typ. 10 centimeters.

Global localization solutions using complex new infrastructure, specific maintenance actions or dangerous signals are not feasible in commercial mass market applications. As a result of this it is not possible to apply most of the solutions known in research community such as cost intensive laser range sensors or vision based systems, which would allow even a simultaneous localization and map building (SLAM) (Burschka and Hager 2004).

Yet some commercial applications need reliable and minimum path revisiting capabilities, which urge the need for low cost global localization systems. Several such systems are known and briefly discussed in the following.

Systems using the principle of triangulation are widely used. An example for such system is CONAC working with rotating laser beacons (Borenstein *et al.* 1996). Problematically here are high hardware costs and the use of spread beacons.

A system described by Peters *et al.* (2000) uses only one beacon with two rotating parallel lasers. The system works with accuracies of 1cm in a circle of 10m around the beacon. Yet the hardware costs are not appropriate for mass market applications.

Several systems using the method of trilateration are known. Possible signals for trilateration methods are radiofrequency (RF) like in the GPS System and ultrasonic waves (US).

Kantor and Singh (2003) described a system using time of flight measurements of RF signals. The weak points of this solution are the need for additional odometry sensors and a complex algorithm for the

localization processing, caused by the low accuracy of the RF measurement of about 2 meters.
Most implementations of trilateration systems make use of the time of flight measurement of an ultrasonic signal. They are in general low cost and have a good accuracy, but need normally at least three spread beacons. These beacons have to be installed by the user, which causes an uncomfortable maintenance effort. An important drawback is also that areas without direct line of sight between the robot and its beacons, the so called shadowed areas, can not be detected or their evaluation depends on additional sensors like odometry and the use of Kalman filtering (Kleeman 1992). Respectively it is not reliable enough to meet the requirements of a robust navigation (Rudolph *et al.* 2004).
Dijk (2004) described two global localization systems using a trilateration technique and a single base station. One system uses three beacons mounted on the base station and the other system incorporates one beacon using wall reflections for position estimation. Although these solutions are rather smart, the achieved accuracies of around 1 meter are not sufficient for map building and advanced navigation tasks. Furthermore complex filter routines and high computational power (PC) are required.
Kim and Kim (2004) developed a system using a single base station for trilateration designed to navigate a commercial floor cleaning robot. They use multiple receivers mounted on the mobile platform to determine the orientation also. Yet the costs for the proposed receiver array are rather high and the achieved position accuracies are in the range of 2 to 28cm and therefore not sufficient as mentioned above.

In this paper an alternative solution for a global localization system is described, which uses a small single base station and the principle of trilateration for determination of the robots pose. It makes use of the time of flight measurement of an ultrasonic signal. It will be shown that the accuracy achieved is high enough to meet the requirements mentioned above.
Furthermore a new approach for the problem of detecting shadowed areas without line of sight between the robot and its base station will be presented.

The paper is structured as follows. It starts with a description of the principle of trilateration. Then the design of the single base station and experimental measurement results are presented. Finally the problem of shadowed areas is discussed and a solution is shown.

2. TECHNICAL OVERVIEW

The proposed localization system is based on the principle of trilateration. Trilateration consists of the determination of at least three distances of a mobile vehicle from beacons for a complete 2D localization. By using only two beacons the position measured is not unique at any point, but with a limitation of the robots range of movement it is nevertheless possible to determine its position.

An important and cheap technique for the realization of this principle is to use an ultrasonic signal for measuring the distances in combination with a radiofrequency (RF) or infrared (IR) signal for synchronizing the robot with its beacons. The time of flight of the ultrasonic signal is directly proportional to the desired distance. Because the sonic speed is quite low the measured signals are easy to evaluate and no expensive hardware is needed for the distance measurement. This type of measurement system is often used in robotics in different designs and it is also the fundament of our approach.

3. SINGLE BASE STATION DESIGN

Typical applications of mobile robots in households require a reliable revisiting of specific areas. The rooms where the robot has to move are rather small and well structured. But, in households it is not appropriate to install a lot of new infrastructure for locating or charging robots. Furthermore applicable systems must be simple and low cost to allow market competitive products. A partially autonomous system with a combined base station for power recharging and localization shows to be a good compromise between system cost and functionality.

Because the measurement accuracy depends highly on the placement of the beacons most authors of trilateration based localization systems use well arranged spread beacons. The system proposed in this paper uses two beacons on the front side of the base station as shown in Figure 1. The fixed baseline $2k$ between the two beacons is typically 40cm.

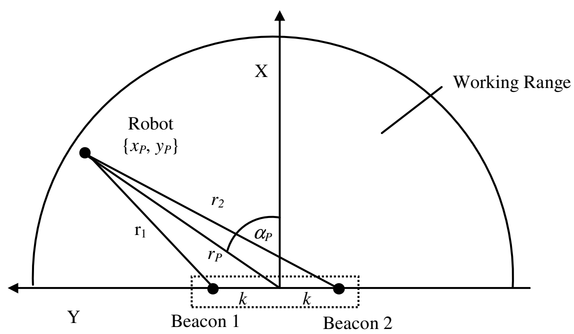

Fig. 1. Definition of the coordinate frame.

The working range of the system is the positive half plane with maximum distances of about 6.5 m of the robot around its base station which is enough to accomplish the desired service tasks in medium sized rooms.
With the definition of the coordinate frame centered in the middle of the beacon baseline (see Figure 1)

the equations to determine the robots position are given by:

$$r_P = \sqrt{\frac{r_1^2 + r_2^2}{2} - k^2} \qquad (1)$$

$$\alpha_P = \arcsin\left(\frac{r_1^2 - r_2^2}{4k \cdot r_P}\right) \qquad (2)$$

$$x_P = \sqrt{r_P{}^2 - y_P{}^2} \qquad (3)$$

$$y_P = \frac{r_1^2 - r_2^2}{4k} \qquad (4)$$

For the active beacons we propose omni-directional ultrasonic transducers and a set of infrared diodes to generate the synchronization signal. The robot is equipped with an omni-directional receiving unit built with reflective cones for both, the ultrasonic and the infrared signal. The beacons are triggered sequentially every 50 ms. To achieve accurate measurements we use receiving circuits detecting the envelope of the IR and the US signal. By this it is possible to get accuracies much better than wavelength based systems.

The accuracy of position determination using ultrasonic signals for distance measurements depends on several known factors. These are mainly shadowing effects by large obstacles, external noise, reflections on the floor or walls due to multipath propagation, windy disturbances or temperature gradients. Shadowing leads to wrong localization results. This is discussed in more detail in the following chapter.

External noise generated by all existing electrical or acoustical sources on and around the robot in particular the robots drives disturbs the US signal. This noise is widely filtered by band-passing and envelope detection of the received signals. Remaining noise can lead to wrong measurements which are rejected by an additional software outlier filter based on prior data.

Reflections especially on floors cause interferences and therefore result in erasing of the signal. This is because the first reflected signal arrives only a few wavelengths after the direct signal and most ultrasonic sensors have a slow transient response. Windy disturbances are confusing the ultrasonic signals and decrease the received amplitudes randomly. Because of these problems, it is essential to decouple the time measured of the ultrasonic signal from its amplitude. For this reason we are not tracing the amplification by time and rather detect the first rise of the incoming sonic signal on a low level which is relatively stable even under bad disturbing conditions like interferences. This is possible only at high signal to noise ratios which can be achieved by a receiving circuit with band-pass filtering and envelope detection. Figure 2 shows the variations of the measured distances to the beacons. It can be observed that the signal variation due to multipath propagation at a distance of around 3.3 m is significantly worse than at other distances. However the absolute error of the measured distance at 3.3 m was not increased compared to other distances.

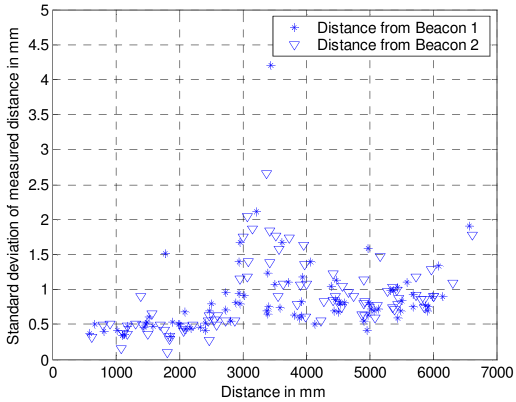

Fig. 2. From the variations of the single distance measurements the high accuracy can be deduced. The increased variations at around 3.3 m are caused by interferences due to multipath propagation of the US signal.

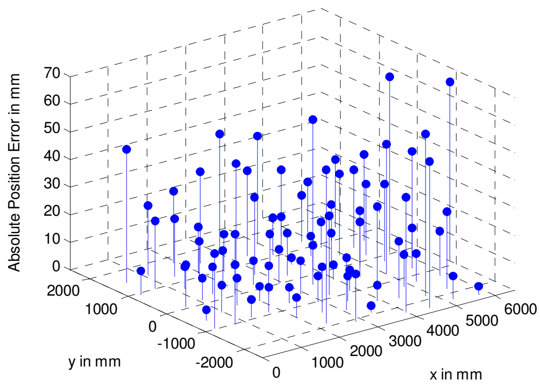

Fig. 3. Accuracy of the absolute position on a set of test samples.

With this approach we can achieve absolute position errors less than 4 cm and a position standard deviation of around 1 cm as shown in Figure 3 and 4. It should be mentioned that the accuracy of positioning the robot in the experiment was in the order of +/-1 cm. The performed measurements are based on 100 values for every point of the used set of test samples.

Because of the close placement of the beacons with respect to each other the determined range r_p of the robot in respect to its base station is much more precise than the determined angle α_p. The absolute range error is less than 1 cm (see Figure 5 and 6) and therefore in the same order as the exactness of positioning the robot on the test samples.

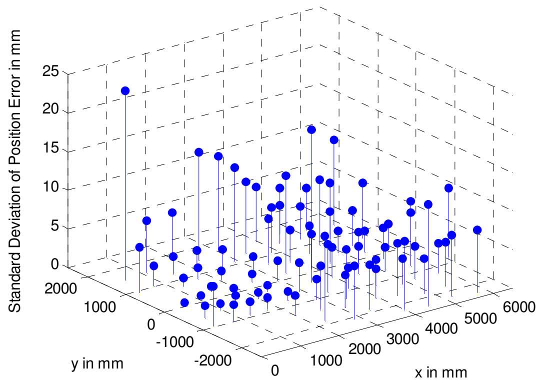

Fig. 4. Standard deviation of the absolute position on a set of test samples.

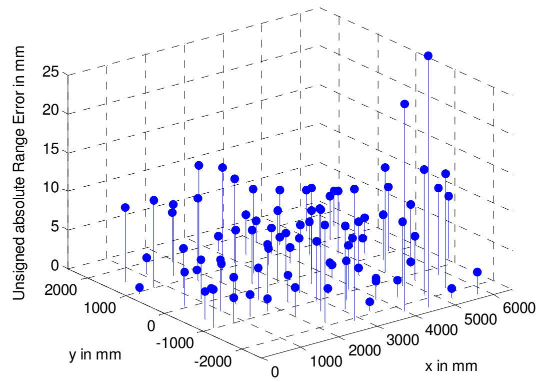

Fig. 5. Accuracy of the range r_p from the base station on a set of test.

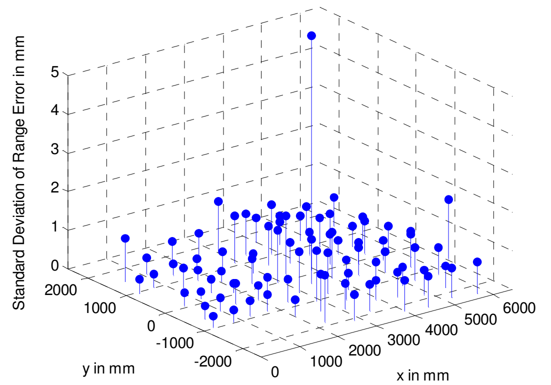

Fig. 6. Standard deviation of the range r_p from the base station on a set of test samples.

In combination with an intelligent motion strategy this fact can be used for a proper navigation. With the achieved position accuracy it is still possible to build up maps of obstacles or other interesting regions without averaging. This is important when using the localization system on a moving robot without additional complicated filter algorithms for position estimation. By using an additional filter algorithm based on successive measurements it is also possible to determine the orientation of the robot.

4. HANDLING OF SHADOWING EFFECTS

The autonomous robot moves through its service area and navigates thereby arbitrarily between distributed obstacles. If the vehicle disappears behind an obstacle and the barrier is higher than the signal line between the base station and the robots receiving unit it comes to shadowing effects. But surrounding obstacles distributed in the area are reflecting the ultrasonic signal from the base station. Because the robot does not know the position of the reflecting obstacles, the determined pose in shadowed areas is erroneous in such a case. To run a robust localization system on a mobile robot these errors have to be detected reliably.

Known approaches assume a minimum number of visible beacons, they use a filter based on prior data (Rudolph *et al.* 2004) or they are integrating additional sensors like odometry and use Kalman filtering (Kleeman 1992). Using filters based on prior data leads to wrong results, if the reflected ultrasonic signal tends to be stable while moving around behind obstacles. Furthermore it is not simple to detect, if the robot exits such shadowed areas. By using inertial sensors or odometry it is a problem to detect the exit of a shadowed area, if the robot moves a long time in it because of the drift error. Furthermore if the used mobile platform as in our case does not support odometry data the method mentioned cannot be applied. We present a solution for this problem using the described localization system only.

Table 1: Reflectance of near infrared light for typical different materials existent in home environments. (Haferkorn, 1994; Hodam, 1974)

Material	**Reflectance ρ [%]**
Grey Wall	0.17…0.63
White Flagstones	0.60…0.80
Brown Wall	0.30…0.38
Black Wall	0.05
Mirror	0.93
Aluminium Mirror	0.89
Glass (3mm)	0.06…0.08
Depolished Glass (3mm)	0.11…0.16
Thin Paper	0.45…0.48

As we are using IR signals instead of RF for synchronization we can benefit from one advantage: the IR signal can not go through obstacles and it is reflected with certain degradation. The infrared reflectance, defined as the ratio of reflected power to incident power depends on the character of the applied materials (see Table 1).

The intensity I_P measured at a point P in a room can be characterized as the sum of the direct signal and all reflections:

$$I_P = \sum_n I_n \qquad (5)$$

The emitted intensity E decreases quadratically with the distances r_n from the base station. Assuming only one effective direct reflection with its reflectance ρ_n for every part of received intensity the relation (5) can be written as:

$$I_P = \sum_n \frac{E \cdot \rho_n}{r_n^2} \qquad (6)$$

As the reflected signal with the shortest distance to the base station gets the measured distance r_0, the ratio of intensity L between the reflections in a shadowed area and the theoretical intensity of the direct signal is given as:

$$L = \frac{\sum_{n=0}^{m} \frac{E\rho_n}{r_n^2}}{\frac{E}{r_0^2}} = \rho_0 + \sum_{n=1}^{m} \left(\frac{r_0}{r_n}\right)^2 \rho_n \qquad (7)$$

The reflections with longer distances are getting continuously insignificant for the measured ratio. If the measured ratio gets under a certain bound a shadowed area is detected. Problems for this approach are highly reflective materials like mirrors, bare metal surfaces or a high amount of reflectors.

This approach has been tested in our laboratory which is a medium sized room with the dimensions of 4x6m. It consisted of white painted walls and an amount of obstacles like tables, chairs, measurement equipment and other stuff. In first experiments we evaluated the intensity measured in the entire room. The result of this measurement in terms of the normalized intensity is shown in Figure 7.

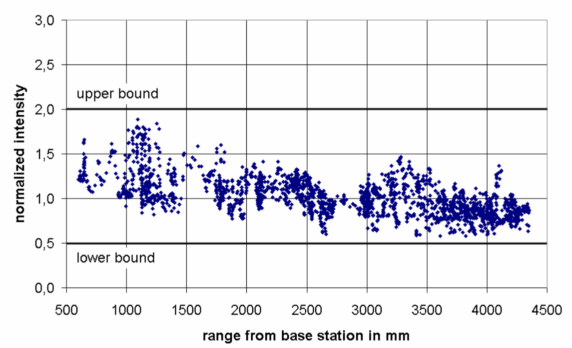

Fig. 7. Distribution of normalized intensity in a test room with upper and lower bound used for filtering invalid measured data.

It can be seen from the data that there are clear upper and lower bounds which can be used for the distinction between areas with and without direct line of sight. The upper bound can be exceeded by erroneous ultrasonic measurements.

In a following experiment we placed obstacles and reflecting materials like mirrors in the room. Figure 8 shows the results of the normalized intensity while the robot moves behind the obstacles. The test data proves the functionality of our approach. Almost all test samples of points measured in regions without direct line of sight are significantly under the bound for the normalized intensity and therefore detectable. Only the reflections caused by a mirror cannot be detected.

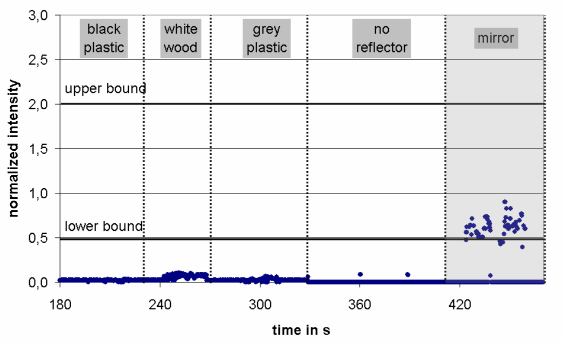

Fig. 8. Normalized intensity measured while the robot was moving around behind obstacles and between different reflectors

This behavior suggests to combine this approach with a filter based on prior data. A combination with certain additional sensors like inertial sensors or odometry is also beneficial, but not mandatory.

With the detection of shadowed areas it is possible to move inside them and to adapt the localization and moving strategy accordingly.

5. CONCLUSIONS

A new global localization system based on trilateration has been presented. It uses only a small single base station with two beacons separated by a fixed small baseline to locate a mobile vehicle. The system uses ultrasonic and infrared signals for the measurement. The main advantage of the presented system is that it is low cost and therefore highly applicable to commercial home robotics because only a single base station is required, which can easily be placed somewhere beside a wall in a room. So no complicated modification of infrastructure is needed. Algorithms for measurement and evaluation are simple and can be easily implemented on a micro-controller.

The localization system has been realized as a laboratory breadboard and worked well under real conditions on a moving mobile device.

The achieved measurement range of 6.5 meters around the base station and the position accuracy of a few centimeters are sufficient for intelligent navigation strategies and map building tasks. The localization accuracy depends on the angle and the distance of the robot from its base station. Polar coordinates can be used beneficially in specific navigation strategies.

It has been proved that the system is operating with the mentioned specifications under disturbed conditions like pulse-width-modulated motor noise and floor reflections.

A new approach for the detection of shadowed areas has been presented. This detection is essential to distinguish between correct and erroneous localization data. This auxiliary information can be used to adapt localization and navigation strategies in the concerned areas.

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